SECTION II. GLOBAL WEATHER RESEARCH

The NASA program of Global Weather Research is to develop an improved capability for making global observations of meteorologically important parameters in order to increase the understanding of the complex processes which influence the large-scale behavior of the atmosphere.

John Theon

THE OBSERVED STRUCTURE OF GLOBAL WEATHER PHENOMENA --

PROSPECTS FOR PREDICTION BASED ON SATELLITE DATA

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Goals of the Research

The goal of our research at Penn State is to combine the observational capabilities of satellite systems with dynamical knowledge and principles to obtain an enhanced capability for understanding and predicting the structure and evolution of global weather phenomena.

Initial research efforts have been directed at identification of cyclic phenomena, such as the zonal index cycle, and the determination of concomitant interactions between the motion and heating fields. These studies have pointed the way to modeling efforts (described in an accompanying report) aimed at determining precisely how transitions are controlled and to development of a conceptual approach for predicting evolution of long-wave structure using satellite data. They also point to some potentially fruitful investigations for the AGCE effort.

Significant Accomplishments and Current Focus of Research

The efforts of the last year have been devoted to study of empirical relations between global scale cyclic phenomena using both conventional and satellite data and to development of the outline of a prediction scheme for large-scale global phenomena.

We have focused our efforts on phenomena associated with the winter-time cyclic behavior of the strength of the zonal component of the westerlies (the zonal index cycle). There are three distinguishable oscillations present in mid- and high-latitude atmospheric flow: short-period (4 days) cycles associated with travelling short waves, the longer cycle (8 to 10 days) associated with the travelling disturbances with wave-numbers five to six, and a longer-period oscillation (20 - 30 days, the index cycle) associated with the quasi-stationary long-waves.

A simple dynamical explanation utilizes the thermal wind concept to argue that reduced eddy transfer of heat during the strongly zonal part of the cycle induces increasing shear of the zonal index and thus instability. The amplifying eddies increase the meridional heat transfer and reduce the thermal gradient, thus reducing the strength of the zonal component and the eddies diminish, starting the cycle again.

The modern mathematical view of this process involves the sequence of bifurcations that appear in forced motion. In general, for weak axisymmetric heating there is a large-scale symmetric solution. With increased heating, the symmetric solution gives way to a three-dimensional periodic solution. With further increase in heating, there is a subharmonic bifurcation to a multiple periodic solution. In Fourier phase space, this subharmonic bifurcation may be represented by the appearance in the longer wavelengths of an energy cycle that oscillates with a period two, three, or four times as long as the basic period. This pattern appears to correspond to a cyclonic period of some 5 days, a subharmonic period of 10 days, and an index cycle of 20 days. The evolution of the energy spectrum of the flow into quite different forms for high and low index regimes has been demonstrated by our empirical studies.

In both the simple dynamical and the mathematical view, the development and maintenance of the longer-period oscillation is a result of the forcing by differential heating exceeding a critical value. This corresponds with the observed fact that the multiple periodic flow is a wintertime phenomenon.

Plans for FY-82 and Beyond

The importance of better resolution of the global scale heating field and the possibility of long-term forecasts are both demonstrated by these observational results.

The main driving force for atmospheric motion on the global scale is the meridional thermal contrast between the low-latitude and polar regions. Our observational results show that variations in meridional heat flux are closely associated with the index cycle. Satellite measurements of outgoing radiation over the polar cap do not appear to be as closely associated with the dynamical processes. However, these are but two processes involved in the entire thermal budget of the polar cap, and we are now attempting to resolve this budget more accurately. Our present opinion is that satellite resolution of the polar cap heat budget may provide important indicators of impending flow transitions.

The oscillation of the energy containing components of the spectrum with both a basic and a subharmonic period suggest that an attempt be made to predict the evolution of these components of the flow. Such a prediction would be aimed, not at local weather conditions, but at global phenomena. Blocking may be viewed as a manifestation of the low-index part of the cycle and such a prediction might forecast both the onset and destruction of major blocking patterns.

An attractive approach is to consider the potential vorticity, which Ertel's theorem demonstrates is a material and global invariant for isentropic and inviscid flow. Changes in potential vorticity thus reflect heating or cooling. The potential vorticity theorem can be converted via approximations valid for small Rossby number and large Richardson number into the quasi-geostrophic equation, which governs an approximate form of the potential vorticity. Within the context of quasi-geostrophic theory, the potential vorticity is determined solely by the temperature field, and thus can be measured by satellite soundings along. Spectral techniques can

then be used to produce predictions of the evolution of the longest waves, utilizing satellite observations of initial fields and heating rates.

It is thus attractive to attempt to construct a spectral model for predicting global weather phenomena. Such a model is certainly not immune to the nonlinear effects that destroy predictability in conventional models, but these problems can be reduced by redefinition of predictability and by suitable parameterization of energy fluxes.

The redefinition is an important and nontrivial step. Predictions of local weather are usually judged on the phase, not the amplitude, of the forecast. Late arrival of a developing cyclone produces forecast error. But if we restrict our interest to a correct prediction of the distribution of spectral energy and ignore phase, then we may have a correct prediction within that framework even though phase errors were serious. We thus take advantage of the fact that spectral energies evolve slowly while phases can vary rapidly with respect to wave number and time. Such a restriction to spectral energies is indeed appropriate in the attempt to determine flow transitions, or the course of the index cycle.

Such a model could not predict evolution of the energy spectrum correctly without at least an approximate version of the spectral energy fluxes from smaller-scale systems. These fluxes depend on phase relations among the Fourier components, but it may be possible to obtain a statistically correct parameterization. We are exploring two innovations in the architecture of spectral models with these ideas in mind. The first invovles use of empirical orthogonal functions to resolve the large-scale dynamics of the flow adequately with a limited number of basic functions. The second is a method of using observed or model results to develop a parameterization of the statistical effect of the smaller components on the large-scales we hope to predict.

Publications

Mitchell, K. E., and J. A. Dutton, 1981: Bifurcations from Stationary to Periodic Solutions in a Low-Order Model of Forced, Dissipative Barotropic Flow. J. Atmos. Sci., 4, 690-716.

Dutton, J. A., 1982: Fundamental Theorems of Climate Theory -- Some Proved Some Conjectured. SIAM Review, in press.

MULTI-PERIOD SPECTRAL MODELS OF GLOBAL PHENOMENA

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SIGNIFICANT ACCOMPLISHMENTS FY-81

A major goal of our effort to utilize satellite observations to understand global weather phenomena is the development of theoretical ideas that can be verified and modified by the use of satellite observations. We have constructed a number of spectral models to test ideas about the atmospheric index cycle and blocking patterns. Eventually we plan to use more realistic patterns of heating which are derived from satellite earth radiation budget observations.

An important part of our theoretical effort has been devoted to understanding the mechanisms whereby the zonally-symmetric Hadley flows break down into the wavelike Rossby patterns typical of mid and high latitudes. The Hadley flow is driven by external radiative heating and to a lesser extent by latent heating a equatorial latitudes. The Rossby pattern seems to evolve when the zonal winds associated with the Hadley regime become baroclinically unstable. Mr. Harry Henderson has successfully developed a two-dimensional spectral model, based on the Boussinesq equations, of the Hadley flow in a cyclindrical geometry which simulates the earth's spherical geometry. Radiative heating is based on observations of Dutton (1976) and eddy viscosity is allowed for. This is one of the first efforts we know of that has been able to model the Hadley regime in as much detail. An analysis was then performed of the stability of the solutions to quasi-geostrophic wavelike disturbances. Mr. Henderson has been able to model in detail the transition over to the Rossby regime by this analysis. Fig. (1) shows in detail the transition region between the regimes and depicts the regions of the Rossby regime that are dominated by various horizontal wavenumbers. We were not able to extend the analysis into the area of large heating or thermal Rossby number Ro_T to investigate the transition back to a symmetric Hadley regime because the solutions for Hadley regime did not converge with large heating.

Studies of the Hadley and Rossby regimes similar to the above in much simpler geometries reveal that the transition between various wavenumbers in the Rossby regime is not a clearcut line as appears in Fig. (1) but occurs in a zone, Lorenz (1962). For instance in the transition between wave n and n+1 there is a region where either wave can dominate and the final transition from n to n+1 occurs along a line which differs from that for the switch-over from n+1 to n. This hysteresis is a common geophysical phenomenon. The atmosphere can probably be characterized as occasionally lying in such zones of transition and the

500 mb flow pattern could be highly transitory. A two-level spectral quasi-geostrophic model has been constructed to look at the detailed structure of the wavenumber transitions in the Rossby regime. So far we have been able to find the non-linear steady Rossby solutions and have discerned the regions of the Rossby regime dominated by each wavenumber. This model is unique in that it is valid for a spherical geometry with full account for the variability of the Coriolis parameter taken into account. We plan to integrate the spectral equations in the vicinity of the transition regions to determine the nature of the flow patterns.

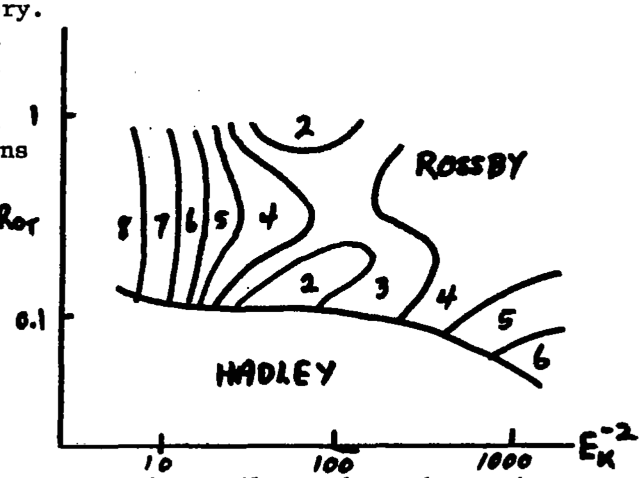

Fig. 1, Hadley and Rossby regimes. Ro_T is thermal Rossby number and E_K is Ekman number.

Two quasi-geostrophic phenomena which we have been especially interested in are the index cycle and blocking patterns. Charney and Devore (1979) have recently shown that the mechanisms governing the establishment of blocking patterns can be simulated with a simple two-layer quasi-geostrophic model. They show that such a model can have under certain conditions multiple steady state solutions and the atmosphere can switch over from one to the other via an instability of an intermediate state which is induced by orography. We have developed a similar model to look at the blocking phenomenon in more detail and to determine whether the index cycle can arise due to an instability of one of the steady states to a periodic solution, a Hopf bifurcation. Some features of our model are:

1) it is spectral with one east-west wavenumber and a mean flow represented at two levels

2) the waves are confined to lie in a mid-latitude β-plane channel bounded at 30 and 60°N

3) orographic forcing of the flow at a single wavenumber is allowed for

4) radiative forcing is specified by an externally-imposed north-south temperature gradient or equivalently a vertical wind shear ΔU_o

5) the model is baroclinic and thus the vertical shear of the mean wind can be altered by the action of the waves but the vertical mean wind U cannot be. The mean wind U is externally imposed and changes in response to momentum forcing across the walls of the channel.

We anticipate that the index cycle is a non-linear, periodic solution of the quasi-geostrophic euqation. Fig. (2) shows the steady solutions to our model for fixed U and ΔU_o as a function of horizontal wavenumber. between wavenumbers 5 and 6 the symmetric Hadley solution becomes unstable and the new steady solution which branches off is singly periodic. When we integrated the non-linear spectral equations, the solution turned out to be doubly periodic - the fundamental period associated with the Roddby period and the second a multiple of that. The solution looks much like the atmospheric index cycle.

We also find that the model can switch over from a Hadley-like solution to a low index blocking pattern a certain critical values of the forcing functions. Fig. (3) gives an example and we shall show examples of the solutions to the time dependent equations as the sudden transition occurs.

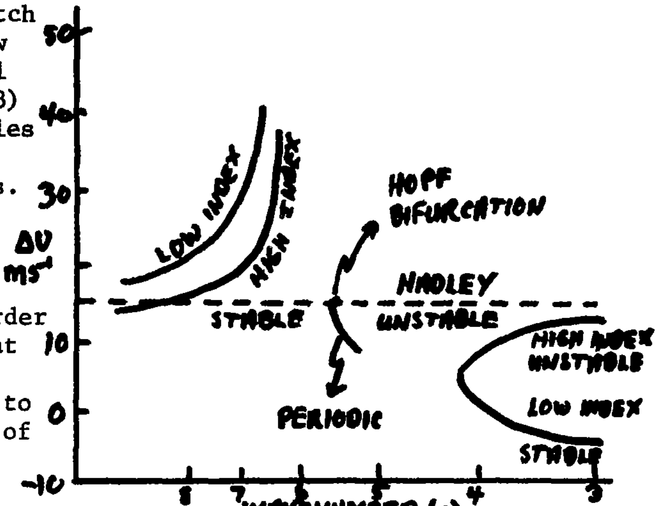

Fig. 2. Steady solutions. $U=\Delta U_o=15$ m s^{-1}.

PLANS FOR FY-82

Now that we have found that a low order spectral model can exhibit a behavior that strongly resembles the atmospheric index cycle and the blocking patterns, we plan to use the models to establish the behavior of these phenomena under a wide variety of conditions. From our observational work we plan to establish the characteristic patterns that the atmosphere assumes prior to the establishment of a persistent blocking situation and then we can utilize satellite observed heating patterns to anticipate blocking situations in the atmosphere. If indeed the index cycle is a multi-periodic phenomenon as our models indicate, we will determine from spectral analysis of satellite temperature and heating patterns the structure of these patterns and then see if the models can duplicate these patterns.

We need to generalize our rather crude spectral models to account for barotropic processes and more realistic wave structures both horizontally and vertically, however, before we can make realistic comparisons with the atmosphere.

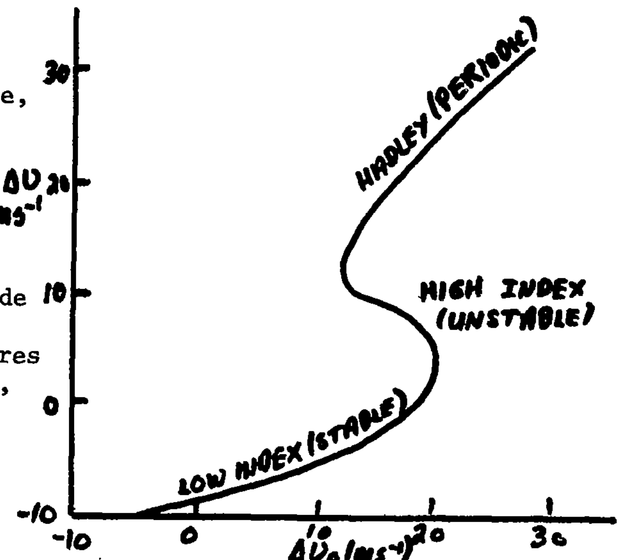

Fig. 3. Steady solutions. Wavenumber 3, $U=20$ m s^{-1}.

REFERENCES

Lorenz, E. N., 1962: Simplified dynamic equations applied to the rotating-basin experiments. J. Atm. Sci., 17, 39-51.

Charney, J. G. and J. G. Devore, 1979: Multiple flow equilibria in the atmosphere and blocking, J. Atm. Sci., 36, 1205-1216.

Dutton, J. A., 1976: The Ceaseless Wind, McGraw-Hill, Inc., 579 pp.

Title: The Role of Latent Heat Release in Baroclinic Waves - Without β-Effect

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Significant Accomplishments FY80:

In this paper we develop the analytical theory of two-level quasi-geostrophic baroclinic waves without β-effect aimed at understanding the role of latent heat release on the development of baroclinic waves.

When the release of latent heat is introduced with pseudo-adiabatic ascent and dry adiabatic descent, the width of the ascending region, a, is different from the width of the descending region, b, and furthermore, a static stability-vertical velocity correlation results in the mean state thickness increasing with time, however, the basic state shear is defined _a priori_, independent of the perturbations, in the formulation of the stability problem. Integro-differential equations for the perturbations are developed. Due to the mass continuity constraint, the unstable waves in the dry and moist regions are stationary in a frame of reference which translates with mean zonal wind at the middle level, and the growth rate in the moist region is equal to that in the dry region, same as in the dry model. Define the parameter $F=2f^2/S_d p_2^2 k_d^2$, where f is the Coriolis parameter, S_d is the static stability in the dry region, p_2 is the pressure at the middle level, and $k_d=\pi/b$. a/b is a function of F. For F>1, two unstable modes appear. The first mode has a narrow region of strong ascending motion and a wide region of weak descending motion (a/b<1), and the second mode has a narrow region of strong descending motion and a wide region of weak ascending motion (a/b>1). As $F\to 1$, the modes become steady and neutral and are characterized by (i) $a/b=(S_m/S_d)^{\frac{1}{2}}$ (S_m: static stability in the moist region), and (ii) $a/b\to\infty$. As $F\to\infty$, the modes are steady and neutral and are characterized by (i) $a/b\to 0$, and (ii) $a/b\to 1$. In comparison with the dry model, the structure of the first unstable mode shows that the ridge and trough of the streamlines shift slightly toward the region of sinking motion, and the warm advection occurs at the node of the vertical motion; while the structure of the second unstable mode shows that the ridge and trough of the streamlines shift slightly toward the region of rising motion, and the cold advection occurs at the node of the vertical motion.

The energetics formula shows the presence of a latent heat release term which contributes directly to the generation of eddy available potential energy. Although this term is small compared to the vertical and horizontal heat transports, latent heat release causes a significant change in the structure of the waves such that large departure in the horizontal heat transport from dry atmospheric values can occur.

The multi-component solution is also discussed. It is stressed that the first harmonic must be present and even harmonics are allowed provided the vertical motion is upward in the moist region of the width a and downward in the dry region of the width b. The solution is not Fourier decomposition in the normal sense, because the odd modes except for the first harmonic are not allowed.

Current Focus of Research Work:

The formulation of the role of latent heat release in baroclinic waves with β-effect is being developed. The preliminary calculations show the disappearance of modes except for one mode in the unstable spectrum for a given basic shear of the mean zonal wind. The problem of the cyclic condition in the wave structure is under investigation.

Plans for FY82:

The continuous model of Eady will be investigated. The extension of the Eady model to three-layer Eady-type model will also be investigated. The purpose is to study the moisture effect in the hierarchy of continuous models, and thus further our understanding of the sensitivity of moisture parameter in various continuous models.

Recommendations for New Research:

The model with the inclusion of the water vapor continuity equation in an initially unsaturated atmosphere should be considered in the new research. This will enable us to consider the conditional convective instability. The cloud equation should also be considered.

Publications:

Tang, C-M., 1980: The influence of the time change of static stability and wind shear on baroclinic waves. Pure & Appl. Geophys. 118, 706-719.

Tan, C-M., 1981: Physical mechanism of baroclinic waves. Review of Selected Meteorological Topics in memory of Dr. Grace Zon-hwa Feng Weigel. (in Chinese)

Saltzman, B., and C-M. Tang, 1981: Effects of variation of static stability and vertical wind shear on the evolution of a primary baroclinic wave. Third Conference on Atmospheric and Oceanic Waves and Stability of the American Meteorological Society, San Diego, California, January 19-23, 1981.

Saltzman, B., and C-M. Tang, 1982: A review of some analytical studies of finite amplitude baroclinic waves, including a new algorithm for the saturation effects of static stability and baroclinicity variations. Submitted to the Special Centennial Issue of the J. Meteor. Soc. Japan).

Tang, C-M., and G. H. Fichtl, 1982: The role of latent heat release in baroclinic waves - without β-effect. (Submitted to J. Atmos. Sci.)

LATENT HEAT AND CYCLONIC SYSTEMS - A CASE STUDY

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ACCOMPLISHMENTS FY-81

Our main objective in FY-81 has been the determination of the effect of latent heating on the vertical motion field and energetics of the storm of March, 1978. We have used the formulation of the quasi-geostrophic omega equation of Hoskins (1975) in which the forcing function is expressed in terms of the horizontal divergence of a vector $\vec{Q}$. The advantage of this technique is that we avoid the problem with compensation between the vorticity and thermal advection effects in the conventional formulation. Our method of inclusion of latent hearing involves a modification of the static stability or equivalently the Brunt-Vaisalla frequency, N, in regions where we anticipate that rising air is saturated. We have picked a region to solve the omega equation surrounding the storm which extends from 25N to 50N and 60W to 110W. Vertical motion due to orography and frictional boundary convergence are allowed for at the lower boundary. The upper boundary condition at 300 mb imposes a solution valid for a source-free omega equation. Lateral conditions are that the vertical motion field is gradient-free. Initial calculations were performed using hand-analysed Q vector fields but were found to be inadequate because of inconsistencies introduced by the analysis. We are now working with fields objectively analyzed by a program originally developed to prepare data fields for a meso-scale forecast model. An example of the results of our calculation is shown in Fig. (1) where the difference between the vertical motion field calculated with and without the effect of latent heating is shown. The boundary of the cloudy area where latent heating was allowed for is the heavy line. Clearly the heating increases upward motion in the cloudy area and there is some compensating subsidence outside the region. From the vertical motion field we have calculated precipitation fields assuming all the condensed moisture falls out of the cloud and none evaporates before reaching the ground. We find that the calculated precipitations are consistently much less than the observed. We have concluded that in spite of the fact that we have chosen winter storms where convective motions should be minimal and the slow quasi-geostrophic vertical motion field should be dominant, meso-scale motions are still present and play an important role in producing the observed precipitation.

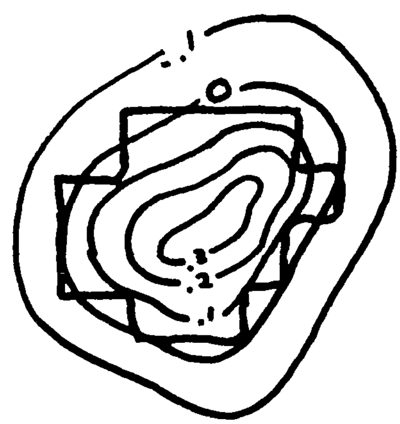

Fig. 1 Vertical velocity (cm s^{-1})

We have used the quasi-geostrophic vertical motions to assess the role of the latent heating for this scale on the energetics of the storm. We have calculated the complete energy budget with and without the effects of the heating to assess the subtle effects of the heating.

Fig. (2) presents the energy cycle for March 25, 0000Z. We have assumed the eddy fields are exactly periodic in the domain of interest to simplify the calculations. Otherwise we would have had to use the formulation of the energetics of Johnson (1970), but we feel that correction due to the non-periodicity of the eddy fields is probably small enough to ignore. The latent heating has only minor effects on the baroclinic conversion of zonal available potential energy into eddy kinetic energy, but it does have an important effect on the conversion of zonal kinetic via mean meridional overturnings. In fact, for one time we found that the sense on this conversion was reversed by the latent heating from direct to indirect. We have carried out this process for the entire life cycle of the March 1978 storm.

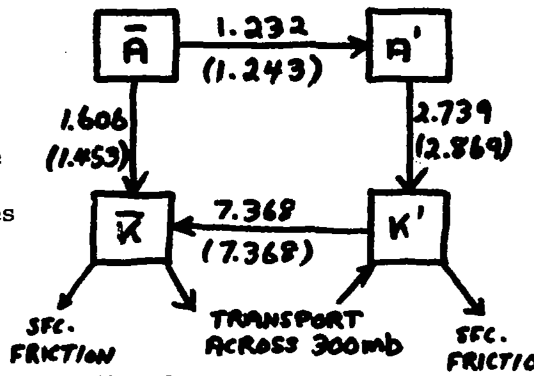

Fig. 2. Energy cycle, March 25, 0000Z

Once we realized the quasi-geostrophic latent heating field was only a small part of the total for this winter storm, we decided to account for other scales of motion in computing the vertical motions. Our first step in this direction was to work with the semi-geostrophic formulation of the equations of motion, where in contrast to the quasi-geostrophic system, horizontal advection by the ageostrophic as well as geostrophic wind is accounted for. Hoskins and Draghici (1977) show that the semi-geostrophic equations can be reduced to an omega equation of the same form as the quasi-geostrophic form in a transformed set of geostrophic coordinates. Normally this transformation cannot be accomplished if the flow field is diabatic, but we have shown that if the latent heating is accomplished by modifying the static stability the transformation can still be carried out. We are currently calculating the semi-geostrophic vertical motion fields for the March, 1978 storm and hope to have results shortly.

A final part of our tasks this year has been to formulate a numerical model to study the effects of latent heating on evolving baroclinic waves. While it is evident that modes of heating other than quasi-geostrophic are clearly important in the synoptic system we have studied, we plan to initially model quasi-geostrophic evolution. After making some preliminary calculations of stationary wave structures with a three-layer model shown in Fig. (3), where the intermediate layer is where the latent heating is only allowed to occur, it has become evident that the depth of the moist layer can be modified by the action of the wave and it is crucial to allowed this to vary during the wave evolution. Air currents rising from the ground where they are unsaturated will become saturated as they rise along their slanted paths in the presence of propagating planetary wave. Thus, the depth of the

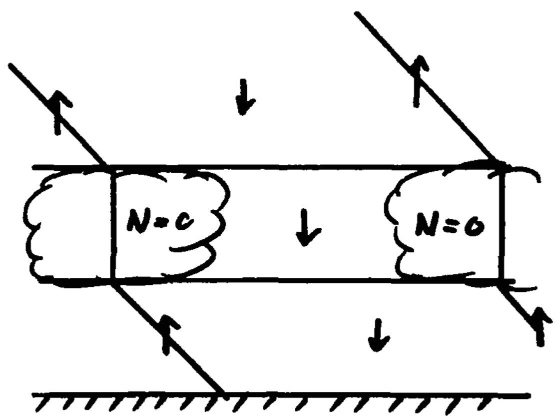

Fig. 3. Three-layer model

saturated layer will vary according to how much moisture is available for the rising air. The low-level field of moisture is in turn controlled by horizontal advection and by the field of precipitation. We are formulating a quasi-geostrophic model which explicitely treats the moisture budget to determine whether - cooperation between the fields of latent heating and the low-level moisture convergence field can significantly alter the evolution a baroclinic wave.

PLANS FOR FY-82

We shall complete the diagnosis of the effects of latent heating on the quasi and semi-geostrophic vertical motion fields for a number of winter storms. We plan to develop schemes for parameterizing the effects of small scale convective motions on the latent heating field. Apparently, one important means of initiating instability is the forced ascent of warm air above warm fronts which renders the lapse rate locally conditionally unstable, Browning (1975).

Our analytical treatment of evolving baroclinic waves will be continued and we plan to study the quasi-geostrophic as well as a hydrostatic equations. We hope with the latter set to examine the implications of various schemes to parameterize the joint effects of low-level moisture convergence and latent heating on the evolving wave structure.

REFERENCES

Hoskins, B. J. and I. Draghici, 1977: The forcing of ageostrophic motion according to the semi-geostrophic equations in as isentrophic coordinate model. J. Atmos. Sci., 34, 1859-1887.

Hoskins, B. J., 1975: The geostrophic momentum approximation and the semi-geostrophic equation. J. Atmos. Sci., 32, 233-242.

Browning, K. A., 1975: An example of rainbands associated with stationary longitudinal circulation in the planetary boundary layer. Quart. J. Roy. Meteor. Soc., 101, 893-900.

Johnson, D. R., 1970: The available potential energy of storms. J. Atmos. Sci., 27, 727-741.

Title: Overview of the Atmospheric General Circulation Experiment (AGCE) Program

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Significant Accomplishments FY81:

In this overview only a brief and non-detailed description of the accomplishments and plans for each research activity of the AGCE Program is given, but the relationships among the activities, and the contributions of the activities to the total AGCE Program, are stressed. The accomplishments and plans of each specific research topic are discussed more fully in the presentations which follow. The approach taken for the AGCE Program has been to proceed on a relatively broad scientific front so that as well as producing engineering specifications for the AGCE instrument, a body of relevant scientific knowledge will be acquired for interpreting and understanding the AGCE data and for relating the data to real atmospheric flows. Such knowledge will also be valuable for the formulation of well-posed experiments with the AGCE instrument. The major accomplishments of FY81 are the following:

1. A Feasibility Study for the AGCE instrument was completed by the Space Division of the General Electric Company at Valley Forge, Pennsylvania.

2. Results were obtained from a numerical, spherical, hydrostatic model of the AGCE and were used as input for the Feasibility Study.

3. Results for the thermally-driven, rotating, axisymmetric, cylindrical annulus flows were obtained from a numerical model based on the Navier-Stokes equations. This model is referred to as the Warn-Varnas code (Warn-Varnas et al., 1978. J. Fluid Mech., 85, 609).

4. A numerical, spherical, axisymmetric model of the AGCE based on the Navier-Stokes equations has been developed. This model is referred to as the Roberts' axisymmetric code. It has been designed to be very flexible and, in particular, it can be easily converted to cylindrical geometry.

5. The Warn-Varnas code was successfully validated using accurate laboratory measurements of stratified spin-up in a cylinder. This work also constitutes a fundamental contribution to rotating fluid dynamics.

6. Studies of the effects of a vertical variation in gravity on baroclinic instability in simple models were completed. The results show that the effects of the radial variation of the dielectric body force are very small.

7. Analytical solutions were obtained for a nonlinear, rotating, Hadley cell and its stability. The model used in this work is a close approximation to the AGCE configuration.

8. The stripping-down of the NCAR Spectral General Circulation Model (GCM) was completed and a regime diagram determined.

Current Focus of Research Work:

The Roberts' axisymmetric code is being used to generate axisymmetric, basic states for a range of parameters of the AGCE. The stability of these basic states will then be determined using a linear stability version of the Roberts' axisymmetric code which is being developed. This work will assist in the preparation of engineering specifications for the AGCE instrument.

Plans for FY82:

1. Completion of the Roberts' linear stability code and determination of regime diagrams for the AGCE.

2. Validation of the Roberts' linear stability code in its cylindrical form against the experimental regime diagrams for the cylindrical annulus flows. These regime diagrams have not yet been derived quantitatively by theory.

3. Construction of a spherical spin-up apparatus for validation of Roberts' axisymmetric code in spherical geometry. This effort should also make fundamental contributions to rotating fluid dynamics.

4. Initiate the development of a spherical, three-dimensional model of the AGCE based on the Navier-Stokes equations.

5. Initiate analytical studies of nonlinear interactions in simple baroclinic models.

6. Continue studies with the stripped-down GCM.

7. Construct a laboratory apparatus which will be the cylindrical analog of the AGCE configuration.

8. Initiate laboratory studies of the dielectric liquids and photochromic dyes recommended by the Feasibility Study.

Recommendations for New Research:

A great deal of flexibility is being built into the computer codes now under development. This will mean that these codes can be used to study laboratory flows in cylindrical and spherical geometry as well as real geophysical fluid flows. It will be possible to assess and to proceed quickly with certain new ideas for studies relating to planetary atmospheric and oceanic flows.

List of Publications Prepared Since June 1980:

1. Eigenvalues of a Baroclinic Stability Problem with Ekman Damping. B. N. Antar and W. W. Fowlis. Journal of the Atmospheric Sciences, Vol. 37, No. 6, pp 1399-1404, 1980.

2. Review of, Rotating Fluids in Geophysics, Academic Press, New York, 1978. W. W. Fowlis. EOS, Transactions of the American Geophysical Union, Vol. 61, No. 39, 1980.

3. Sullivan's Two-Celled Vortex. F. W. Leslie. American Institute of Aeronautics and Astronautics Journal, Vol. 18, No. 10, p 1272, 1980.

4. Theoretical Regime Diagrams for Thermally Driven Flows in a Beta-Plane Channel in the Presence of Variable Gravity. J. E. Geisler and W. W. Fowlis. NASA Technical Memorandum 78316, 18 pp, 1980.

5. Baroclinic Instability of a Fluid in A Rotating Channel. B. N. Antar and W. W. Fowlis. (Abstract) Bulletin of the American Physical Society, Vol. 25, No. 9, p 1077, 1980.

6. The Applicability of the Piecewise Linear Current Profile in the Baroclinic Instability Problem. J. M. Hyun. Journal of the Meteorological Society of Japan, Vol. 58, No. 6, 1980.

7. Baroclinic Instability with Variable Static Stability - A Design Study for a Spherical Atmospheric Model Experiment. A. C. Giere and W. W. Fowlis. Geophysical and Astrophysical Fluid Dynamics, Vol. 16, pp 207-224, 1980.

8. Separate and Combined Effects of Static Stability and Shear Variation on the Baroclinic Instability of a Two-Layer Current. J. M. Hyun. Journal of the Atmospheric Sciences, Vol. 38, No. 2, pp 321-333, 1981.

9. Baroclinic Instability of a Rotating Hadley Cell. B. N. Antar and W. W. Fowlis. Accepted for publication in the Journal of the Atmospheric Sciences, October 1981.

10. Numerical Solutions for the Spin-Up of a Stratified Fluid. J. M. Hyun, W. W. Fowlis and A. Warn-Varnas. Accepted for publication in the Journal of Fluid Mechanics.

11. A General Solution of the Eady-Type Equation of Baroclinic Instability. A. C. Giere and W. W. Fowlis. Accepted for publication in Geophysical and Astrophysical Fluid Dynamics.

12. Numerical Solutions for the Spin-Up of a Homogeneous Fluid from Rest. J. M. Hyun, F. W. Leslie, W. W. Fowlis and A. Warn-Varnas. In preparation.

CALCULATIONS OF AXISYMMETRIC FLOW

AND ITS STABILITY FOR THE AGCE MODEL

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Accomplishments of FY 81

The ultimate purpose of this research is to determine, by the use of numerical primitive equation models, where baroclinic waves might be expected in the AGCE apparatus. This will be accomplished by using an axisymmetric primitive equation model to compute, for a given set of experimental parameters, a steady state axisymmetric flow and then testing this axisymmetric flow for stability using a linear primitive equation model.

During this year we have completed construction and testing of the axisymmetric model. Calculations using this model have been completed for various rotation rates and temperature distributions in the AGCE apparatus. These calculations have been used to aid in design considerations of the AGCE equipment.

The model used to compute the steady state axisymmetric calculations does so by first integrating the traditional hydrostatic version of the primitive equations until a steady state is reached. Then additional terms are added to the diagnostic equation for pressure from the vertical equation of motion (in particular the friction and advection terms) and the model is again integrated to steady state (this second steady state is reached rather quickly). At steady state, this new flow is equivalent to that which would be obtained by a full nonhydrostatic model yet the cost is considerably less than that required of a fully nonhydrostatic calculation. Furthermore a comparison of the nonhydrostatic and hydrostatic steady state solutions show that except for very small regions near the poles and equator, the hydrostatic and nonhydrostatic solutions are virtually identical. The primary difference is in the width of the narrow vertical jets that form at the pole and equator. These results suggest that a full nonhydrostatic model for computing steady state solutions is unnessary.

We also have completed a linear model of the AGCE experiment in which only a single wave in the zonal direction is retained. Unfortunately, at the time of this writing this model has not yet been fully validated, and even preliminary results are not yet available. This model will be used to determine the stability of the axisymmetric flows calculated by the axisymmetric model.

Our current efforts are to complete testing the linear model and then use these models to obtain at least a crude estimate of the regime diagram for AGCE. Our plans for FY-82 are, therefore, to complete the calculations necessary to produce this diagram.

Recommendations for New Research

The regime diagram that will be produced under the current research has a pole-to-equator temperature difference which is the same on the inner sphere as on the outer. Our research has shown that flows more like the earth's atmosphere occur when the outer sphere is isothermal. Because the temperature gradients on the outer sphere are zero we would expect that the wave activity and hence flows within the apparatus would be quite different from the flows when temperature gradients are maintained on both spheres. Comparing the flows in the two configurations may provide further insight into the dynamics of the baroclinic waves. Therefore we recommend preliminary theoretical research into nature of the flows, including regime diagrams, in this alternate configuration.

In addition the AGCE apparatus offers a possible means for conducting simplified experiments to isolate and understand how certain dynamic processes force and maintain eddies in the General Circulation. Such experiments are currently possible only with general circulation models. For example, experiments to study the effects of mountains and land-sea contrast on the transient ultra-long waves may be possible in an experiment similar to AGCE. These might be patterned after general circulation model experiments which we are currently constructing for other contracts.

List of Publications

To date no publications concerning this research have appeared in the literature. However, we are currently preparing a paper describing our hydrostatic and nonhydrostatic axisymmetric calculations. We hope to submit this paper to a journal in the next couple of months.

Title: Cylindrical Numerical Models: Axisymmetric Basic States

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Significant Accomplishments FY81:

We have in our possession an axisymmetric, cylindrical code developed by Alex Warn-Varnas (Warn-Varnas et al., J. Fluid Mech., Vol. 85, 609, 1978). This code is based on the Navier Stokes equations and is for incompressible, Boussinesq flow. The equations and the initial and boundary conditions are finite differenced on a staggered mesh with nonuniform grid spacings. The resulting time-dependent difference equations are solved by a time-marching procedure. The stretching is used for boundary layer resolution. The pressure is found from a Poisson equaiton obtained from a divergence equation and is solved using an ADI iterative approach.

Using the Warn-Varnas code, a number of axisymmetric states for the thermally-driven, rotating, cylindrical annulus flows were computed over a range of parameters. The results were compared with earlier computations by G. P. Williams (J. Atmos. Sci., Vol. 24, 144, 1967 and J. Atmos. Sci., Vol. 24, 162, 1967). Excellent agreement was obtained. The Warn-Varnas code was also used to compute axisymmetric flows for the cylindrical analog of the AGCE configuration for input to the Feasibility Study.

It was originally our intention to use the Warn-Varnas code to compute regime diagrams to assist in preparing engineering specifications for the AGCE instrument. The plan was to prepare a linear stability version of the code and then using both versions to compute axisymmetric basic states and their stability for the cylindrical annulus flows. This work would have enabled us to validate the codes against the experiment regime diagrams for the annulus flows and this would have been a scientific contribution in its own right. Finally, the codes were to be converted to spherical geometry and a regime diagram for the AGCE prepared. However, further examination revealed that the Warn-Varnas code was somewhat out-of-date and that newer techniques would allow for faster and more flexible codes. We decided to determine the theoretical regime diagrams for the AGCE apparatus using spherical codes built from scratch and incorporating the latest ideas.

Current Focus of Research Work:

The Warn-Varnas code is no longer being used for the AGCE design studies.

Plans for FY82:

The Warn-Varnas code will still be used for spin-up and other fundamental rotating fluids studies.

Title: Utilization of Satellite Cloud Information to Diagnose the Energy State and Transformations in Extratropical Cyclones

Research Investigators Involved:

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George H. Fichtl, ES 83/MSFC, AL 35812, 205-453-0875

Accomplishments FY81 and Current Focus:

Since this project is only three months old, accomplishments to date are limited. Work over this period has concentrated on the selection of extratropical cyclone cases to analyze and the reduction of conventional data. Foremost among the criteria for making these selections are that

(1) the cases occur over a region and time period of abundant conventional meteorological data, and
(2) the cases be cyclones with widespread and significant precipitation and latent heat release.

With these criteria in mind, the first case chosen was one of dramatic cyclone development over the central United States during the period 9-11 January 1975. Standard 0000 and 1200 GMT rawinsonde data, hourly precipitation data, and National Meteorological Center sea level pressure, upper air isobaric, and radar analyses have been assembled for this case. All temperature, height, moisture, and wind data have been checked and gridded to a 140 km grid. In addition a search is in progress to identify the types of satellite data available.

Finally, to further test the quality of the data set, higher order quantities contained in the kinetic and available potential energy budgets are being computed.

Plans for FY 82:

Work will continue on selection of appropriate case studies and preparing data sets. These sets will be used to initiate calculations of complete energy budgets.

Leading these calculations will be the determination of diabatic heating fields and the adiabatic and diabatic components of the vertical motion. These in turn will be used to calculate the generation and release of available potential energy and vertical flux divergences of available potential and kinetic energy in order to evaluate the impact of diabatic heating on extratropical cyclone evolution. In all of this the effectiveness of satellite data in improving the heating estimates will be examined.

Spherical Numerical Models for the AGCE: Axisymmetric Basic States and their Stability

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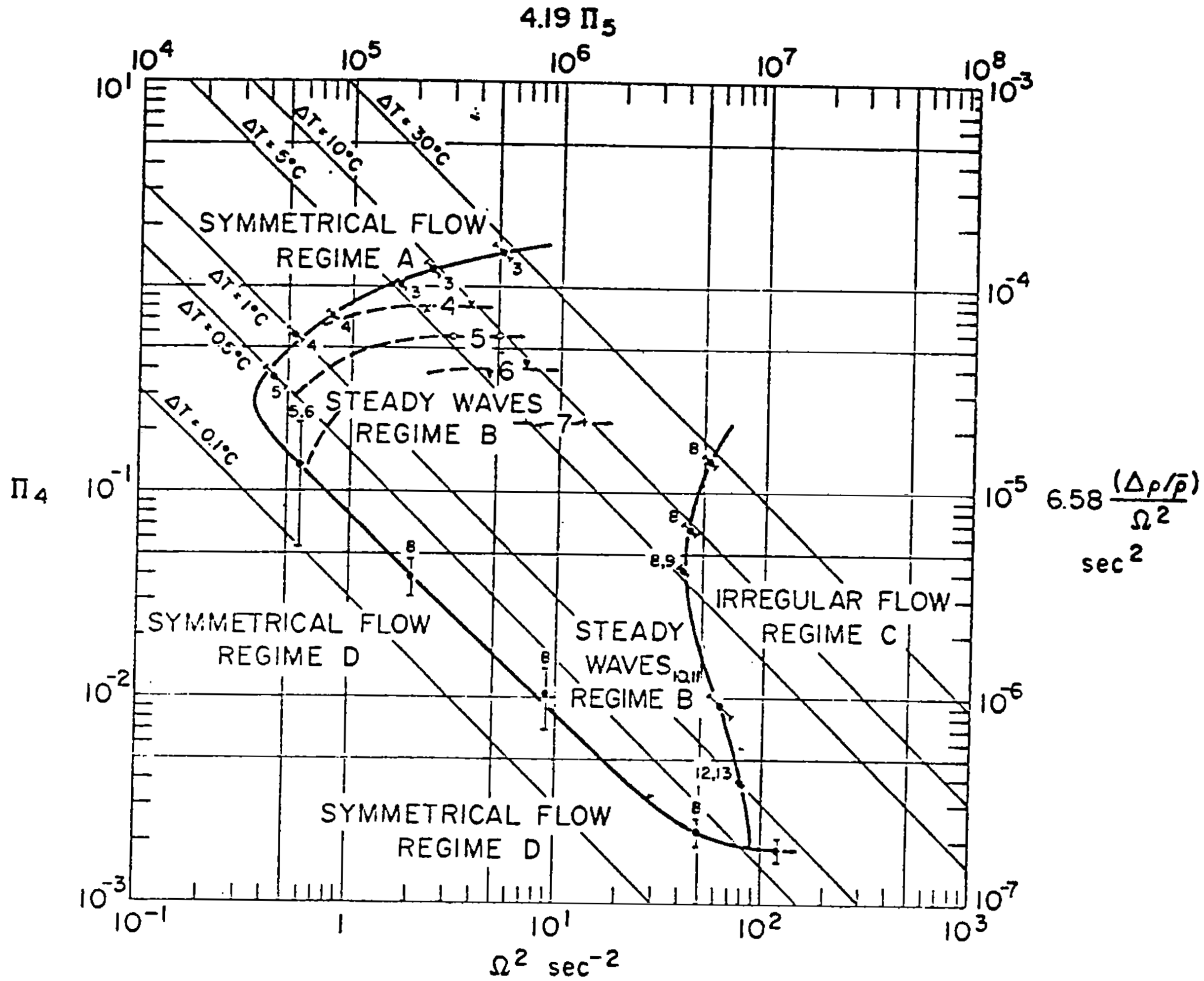
FY-81 Accomplishments

This section of the AGCE program began in March, 1981. Two computer codes are involved. The first calculates axisymmetric steady flow solutions. The second will determine the growth or decay rates of linear wave perturbations with different wave numbers. Growing solutions indicate instability. The results will be important for AGCE design, since the apparatus should allow experiments well within the unstable (wave) regime.

The figure on the next page is an experimental regime diagram for a particular cylindrical annulus geometry, as the rotation rate and temperature difference are varied. Our objective is to obtain similar theoretical diagrams for the boundary between the symmetric and wave regimes, with various proposed AGCE configurations. The codes can be validated by application to the cylindrical geometry and comparison with the experiments.

Results are required for a very wide range of AGCE design parameters and operating conditions. Thus efficient numerical algorithms are required to keep the computing requirements within reasonable bounds. We use nonuniform meshes and implicit iterative methods. These methods are related to time stepping, but with the time step different for each variable and mesh point.

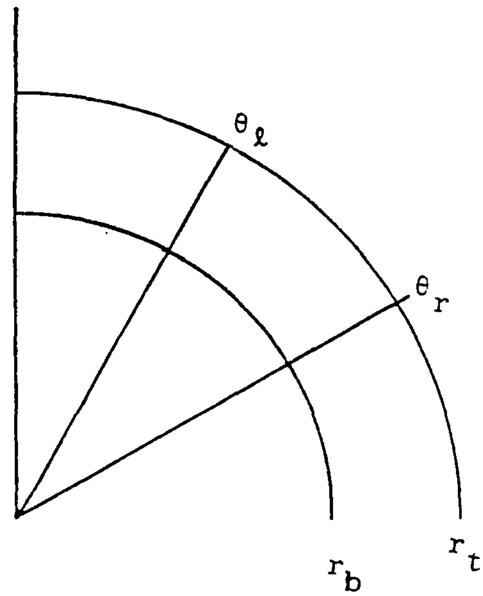
The domain for the codes is shown below. With appropriate choices of the boundary parameters, we can model a spherical shell, a hemispherical shell, a cylindrical annulus, or other geometries. The codes also allow for any combination of dielectric, terrestrial (axial) and centrifugal gravity. There is further flexibility in the boundary conditions on the flow (no-slip or free-slip) and temperature (imposed value or insulated). This flexibility is an important feature for design and validation purposes and for future applications.



$$\Pi_4 = \frac{gd(\Delta\rho/\bar{\rho})}{\Omega^2(b-a)^2}, \quad \Pi_5 = \frac{4\Omega^2(b-a)^5}{\bar{\nu}^2 d}, \quad \Pi_6 = \frac{\bar{\nu}}{\bar{\kappa}}.$$

a = 3.5 cm, b = 6 cm, d = 10 cm

Experimental Regime Diagram for Free-Surface Annulus Convection, using water.

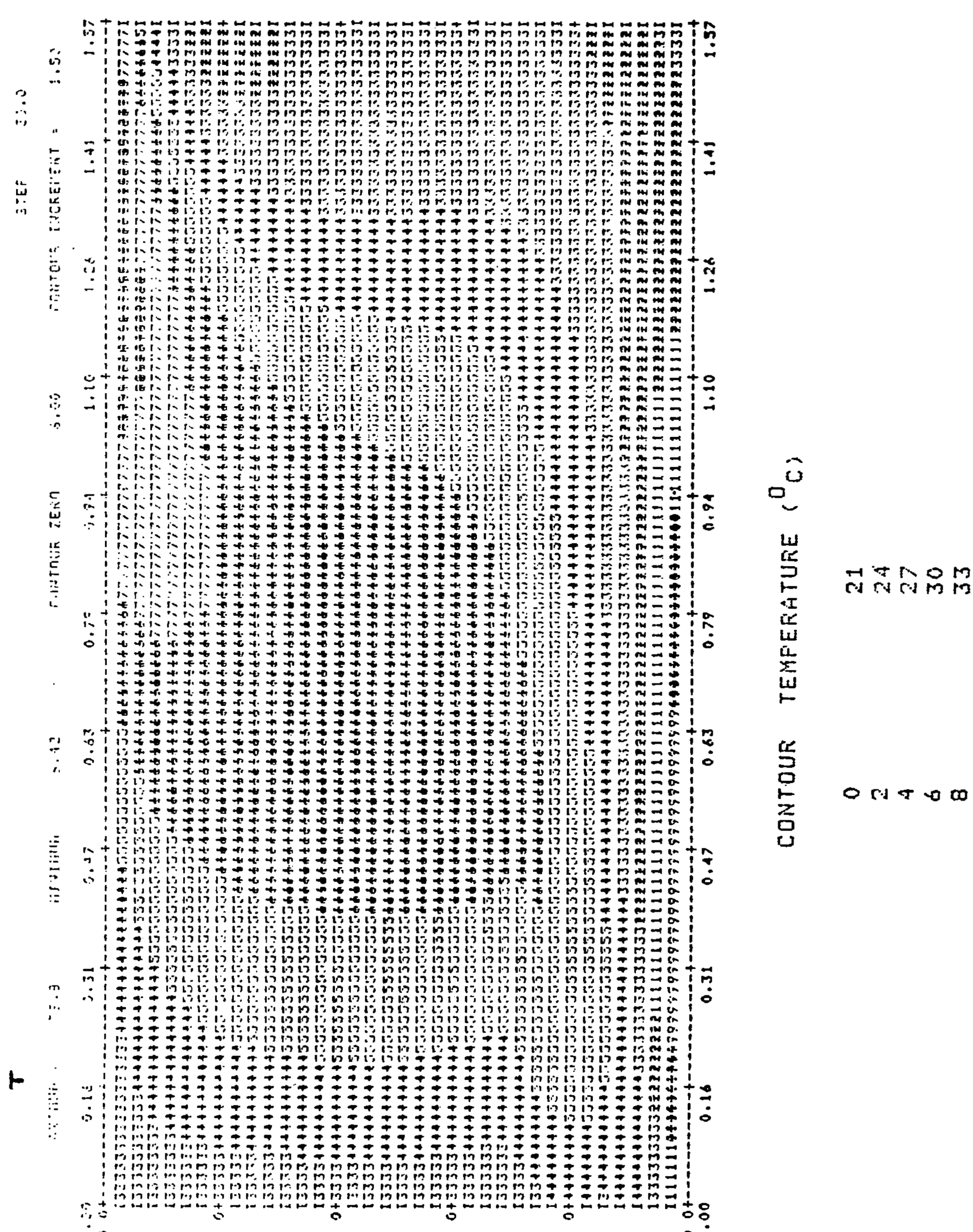


Case	Values
Spherical layer	$\theta_\ell = 0$, $\theta_r = \pi$
Hemisphere Cap	$\theta_\ell = 0$, $\theta_r = \pi/2$
Cylindrical Annulus	$\theta_\ell = \rho_\ell/R$, $\theta_r = \rho_r/R$ $r_b = R$ $r_t = R + h$

The Computational Domain and Special Cases

Current Focus

The steady state code is now almost fully operational. A steady state temperature solution is displayed below, for a hemispherical cap with radii 3 cm and 4 cm. The polar temperatures are 15°C and 25°C at the bottom and top; the corresponding equatorial temperatures are 25°C and 35°C. The flow has produced an ascending thermal plume at the equator and a descending plume at the pole. The graphics and numerical methods are being improved.



FY-82 Plans

The numerical algorithms for the linear stability code will be finalized. The planned iterative method is related to time stepping the linearized equations, with an unknown growth or decay rate which is corrected each iteration. The time step is different for each variable and position. We expect the code to become operational by the middle of the year.

The two codes will be combined, to operate together in an efficient way, and generate regime diagrams. They will be validated on the annular geometry, and then applied to a series of projected AGCE designs and parameter ranges.

Recommendations for New Research

If the validations are successful, these codes will constitute an important NASA tool for studies in convective motions and baroclinic stability. They can potentially be used not only in support of AGCE design, but also to validate analytic theories and to interpret experimental and observational measurements related to atmosphere and ocean flows.

Publications

Roberts, G. O., 1981: Axisymmetric AGCE Flows and their stability. Proceedings of the April AGCE Conference, in Boulder, CO.

Three-Dimensional AGCE Numerical Model

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FY 82 Plans

The planned computer code will calculate steady and time-dependent AGCE flows, using the full nonlinear three-dimensional equations. Proposed experimental settings will be checked first, using model runs. Then actual experimental results (laboratory and Spacelab) will be compared with model predictions. This interaction between experiment and model will be very valuable in determining the nature of the AGCE flows and their relationship to analytical theories and to actual atmosphere dynamics.

The planned program will start in November, 1981. During the first year the numerical procedures will be determined, and code implementation will begin. We plan to complete and test the code in the second year. Validations will be performed in the third year, and proposed AGCE experiments will be modeled.

Recommendations for New Research

Beyond the scope of the proposed three-year program, we recommend numerical studies of the linear stability of steady three-dimensional baroclinic flows. The annulus experiments suggest that a small change in rotation rate or temperature difference can destabilize a steady nonlinear three-dimensional wave, with perhaps four waves, and produce either a steady solution with a different number of waves or an amplitude or wave number vacillation. Global atmosphere dynamics can show similar phenomena, and they may also occur in the AGCE tests. A linear stability model could aid in understanding these effects.

Title: Linear and Nonlinear Spin-Up/AGCE Numerical Model Validation Studies

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Significant Accomplishments FY81:

A large computer code (Ref. 1) has been obtained and amended in order to study fundamental problems in rotating fluid dynamics. This code uses the primitive Navier-Stokes equations in axisymmetric form and employs finite-difference techniques on variable grids. The numerical results have been verified for spin-up of a homogeneous fluid in a closed cylinder (Ref. 1). Efforts have been made to resolve the spin-up flow of a stratified fluid in a cylinder. The numerical solutions were checked against the accurate disturbance-free laser Doppler measurements, and good agreement was obtained. It has been established that viscous diffusion in the interior, arising from the enhanced flow gradients in stratified spin-up, is the cause of the discrepancy between theory and experiments.

Current Focus of Research Work:

An investigation is being conducted on the strongly nonlinear problem of spin-up from rest of a homogeneous fluid in a cylinder using the aforesaid numerical code. The numerical results were compared against the laser Doppler measurements, and close agreement was found. The correct location and the viscous structure of the moving shear front are examined with the aid of the accurate comprehensive flowfield data. The basic assumptions adopted in the classical Wedemeyer model (Ref. 2) are reevaluated in light of the present numerical results. The limitations of the classical Wedemeyer model and its extensions are clarified, pointing to the difficulty in formulating the exact nonlinear Ekman compatibility conditions in finite geometry.

References

1. Warn-Varnas, A., Fowlis, W. W., Piacsek, S. & Lee, S. M. 1978 Numerical solutions & laser-Doppler measurements of spin-up. J. Fluid Mech. 85, 609-639.

2. Wedemeyer, E. H. 1964 The unsteady flow within a spinning cylinder. J. Fluid Mech. 20, 383-399.

Plans for FY82/Recommendations for New Research:

Plans are underway to examine numerically the spin-up flows in a cylinder when the top and bottom discs are given different final rotation

rates. Of particular interest will be the spatial and temporal dependence of the Ekman pumping conditions. When the fluid is stratified, this problem will illuminate the transient behavior approaching the steady state which is used as the basic state flow in baroclinic instability studies. In conjunction with the planned numerical investigation, laboratory apparatus will be designed which will provide accurate experimental verifications for the numerical results.

List of Publications Prepared Since June 1980:

J. M. Hyun, 1980: The applicability of the piecewise linear current profile in the baroclinic instability problem. J. Meteor. Soc. Japan, 58, 544-459.

J. M. Hyun, 1981: Separate & combined effects of static stability & shear variation on the baroclinic instability of a two-layer current. J. Atmos. Sci., 38, 322-333.

J. M. Hyun, W. W. Fowlis & A. Warn-Varnas, 1981: Numerical solutions for the spin-up of a stratified fluid. Accepted for publication in J. Fluid Mech.

J. M. Hyun, F. W. Leslie, W. W. Fowlis & A. Warn-Varnas, 1981: Numerical solutions for the spin-up from rest. To be submitted to J. Fluid Mech.

J. M. Hyun, 1981: Spin-up of a stratified fluid in a cylinder with conducting sidewall. Under preparation.

Theoretical Studies of Baroclinic Flow Related to the AGCE

By

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Significant Accomplishments FY-81: A study of the baroclinic instability of a rotating Hadley cell was completed and a paper reporting the major results of this study will appear in JAS in October 1981. In this study we investigated the influence of a prescribed horizontal, as well as vertical, temperature gradients on the baroclinic instability of a rotating fluid layer. Although the model was for a simple flat layer of fluid, it incorporated several features of the spherical AGCE model. Information is being gained on the design criteria of AGCE using this simple model.

The above mentioned model was extended to investigate the symmetric baroclinic instability of a rotating Hadley cell. Results are being gathered using this model and a paper summerizing these results is being prepared for publication. The most attractive part of the model is its simplicity while incorporating essential physical features of a realistic system. This is proving to be of great value in further understanding the symmetric baroclinic instability mechanism and its consequences. A laboratory experiment based on this model is being prepared at NASA/MSFC to test and verify some of the results of the analytical model.

A numerical code was developed to solve for the symmetric flow field in a rotating spherical annulus to model the symmetric basic state of AGCE. The numerical technique used is a mixed spectral finite difference method. A specific spectral expansion was developed and incorporated in the code. The coding is not yet finished and work is continuing on it.

Current Focus of Research Work: Work is underway to extend and use the simple basic state analytical profile which was developed for the rotating Hadley cell to study the nonlinear baroclinic instability mechanism. Although there is a great deal of work on nonlinear baroclinic instability, it is felt that the present effort will augment and fill some important gaps in the present understanding of this field. It is also hoped that the results of this study will help in better understanding of the nature and mechanism of finite amplitude waves that will exist in the AGCE. This study is both analytical and numerical.

Work is underway to extend the rotating Hadley cell model and numerical code to help in the understanding of specific circulation models in shallow seas.

Plans for FY-82: To finish the numerical code for the symmetric basic state of the spherical annulus. To continue the nonlinear stability analysis for the rotating Hadley cell. To perform the experiments on the symmetric baroclinic instability.

List of Publications Prepared:

1. Antar, B. N. and W. W. Fowlis: Eigenvalues of a Baroclinic Stability Problem with Ekman Damping. J. Atmos. Sci., 37, 1980, pp 1399-1404.

2. Antar, B. N. and W. W. Fowlis: Baroclinic Instability of a Fluid in a Rotating Channel, Bull. Am. Phys. Soc., 25, 1980, 1077.

3. Antar, B. N. and W. W. Fowlis: Baroclinic Instability of a Rotating Hadley Cell, J. Atmos. Sci, 38, 1981, xxx-xxx.

4. Antar, B. N. and W. W. Fowlis: Baroclinic Instability of a Rotating Hadley Cell: Symmetric Instability. In preparation.

Title:

Flow Regime Studies with a Simplified General Circulation Model

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Significant Accomplishments FY-81:

In the Atmospheric General Circulation Experiment (AGCE) apparatus a fluid is confined between co-rotating spheres in the presence of a simulated radial gravity and a meridional temperature gradient on the inner sphere. This situation is much closer to the atmosphere than is the traditional laboratory analogue, which consists of an annulus of fluid confined between co-rotating cylinders oriented parallel to terrestrial gravity. We have modified an atmospheric general circulation model to the point where it looks as close as possible to the AGCE apparatus (no clouds, no radiative transfer, smooth lower boundary, etc.) We are presently operating this model in the laboratory experiment mode, treating the meridional temperature gradient and the rotation rate as parameters at our disposal. Our objective is to acquire the basic knowledge necessary for application of the AGCE data to the understanding of large-scale atmospheric dynamics.

In the traditional (that is, annular geometry) laboratory experiments the horizontal temperature gradient and the rotation rate appear in dimensionless parameters called the thermal Rossby number and the Taylor number, and the observation as to whether or not waves are present is noted in a diagram (called the regime diagram) with these two dimensionless parameters used as ordinate and abscissa, respectively. The curve in this diagram separating the region where waves occur from the region where waves do not occur is referred to as the stability boundary. Linear baroclinic instability models with Ekman damping present have been successful in reproducing the shape and (to some extent) the location of the stability boundary found in the annulus experiments.

Our main research accomplishment this year has been to find and map out the features of a stability boundary that exists in our modified general circulation model. To our knowledge this is the first time that this major feature of a regime diagram has been derived from numerical experiments using a fully nonlinear primitive equations model on a sphere. This stability boundary appears to have the same characteristic shape as that of the annulus experiments, and its location in the regime diagram is roughly in accordance with predictions from a linear baroclinic instability model on a beta plane.

The square root of Taylor number, used as the abscissa in the regime diagram, contains among other things the inverse first power of the viscosity coefficient. Consequently, the location of the stability boundary in the regime diagram is sensitive to the amount of viscosity present. Our model contains a horizontal eddy viscosity and a vertical eddy viscosity. We are presently nearing the end of a series of experiments designed to assess the relative effects of these two types of damping on the location of the model stability boundary. Our tentative conclusion is that the vertical eddy viscosity is dominant. We have recently become aware that the vertical eddy viscosity as it exists in the model really has two parts: the stress at the lowest model grid point is specified by a quadratic surface drag law with fixed drag coefficient and the stress at all other model levels goes like the product of a diffusion coefficient K and the vertical shear of the horizontal flow. Many of our results to date, including our assessment of the location of the stability boundary in the regime diagram, have been obtained from runs in which we varied K but failed to vary the surface drag coefficient. We have eliminated this problem by specifying that the stress go like K times shear everywhere and imposing a no-slip condition at the lower boundary. We are presently running many of our cases over again with this new boundary layer formulation, anticipating that this new modification will change the location of the stability boundary but will not significantly alter its shape.

Plans for FY-82:

Once we have the firmly established the shape and location of the stability boundary and understand in terms of model dynamics why it is where it is, we will go on to explore specific features and characteristics of wave fields present. First on our list will be a search for the region in the regime diagram where wave vacillation occurs, then we will try to map out the subregions where the period of the vacillation is long and where it is short. We will analyze individual cases of vacillation and examine the energy cycle, comparing our results with what is known from the vacillation studied in the annulus experiments. We will also seek to find subregions in the regime diagram where the wave field is dominated by a single wave and at the other extreme, where so many waves are present that the flow field is irregular. As a further extension of our work which will make full use of all the data generated from our many model runs, we propose to regard our model as a climate system whose external parameters are an imposed meridional temperature gradient and rotation rate and will seek to define the climate by systematically assembling mean quantities and fluctuation statistics from these data.

Publications since June 1980:

None.

Title: The AGCE Instrument Feasibility Study

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Significant Accomplishments FY81:

Preliminary scientific design calculations had determined that the AGCE apparatus has to be different from the GFFC in three major respects:

1. A large, stable, radial temperature gradient with associated inwards heat flow has to be maintained.

2. The diameters of the spheres have to be increased.

3. A larger value of the liquid dielectric constant and/or a higher voltage are required.

It was also clear that it was not practical to scale-up the optical system of the GFFC to accommodate the larger spheres required for the AGCE; new concepts for the flow and temperature measurement were needed. These requirements led to a Feasibility Study which was awarded to the Space Division of the General Electric Company, Valley Forge, Pennsylvania, January 81. The task list was as follows:

1. Dielectric liquids survey
2. High voltage and high frequency sources
3. Dust removal
4. Observation of the flow and data storage
5. Optical field of view
6. Thermal control
7. Control of the total apparatus
8. Material for the outer sphere
9. Configuration of the total apparatus
10. Design and fabrication costs

The Feasibility Study was completed during July 81 and much was accomplished. The following is a summary of the results.

1. A new concept for the flow and temperature measurement using an optical scanner was worked out. This device will be able to make measurements to the specified accuracy and will not require the large lenses of the GFFC.

2. Several high dielectric constant liquids with compatible photochromic dyes were recommended. These liquids satisfy the many other constraints of the AGCE apparatus, but their relatively high values of electrical conductivity may still present problems.

3. A voltage source of up to 15,000 volts rms which meets our specifications is feasible.

4. The optical and thermal specifications for the outer sphere mean that sapphire is the only suitable material. A large enough boule can be grown to meet our size requirements but the hemisphere will have to be cut from the boule such that the optic axis will rotate in the equatorial plane. This in turn means that birefringence effects will be present in the scanner but only a small degradation of the measurement accuracy will result.

5. The remaining tasks, dust removal, thermal control, total apparatus control and apparatus configuration can all be accomplished with standard technology. It was recommended that all data be telimetered directly to ground; this will allow for real time examination by the scientific investigation and hence for more flexibility with the AGCE experiments.

Current Focus of Research Work:

We are continuing to assess the Feasibility Study.

Plans for FY82:

In general, in liquids, a high dielectric constant is associated with a high electrical conductivity. Purification can reduce the conductivity. Purification procedures recommended in the Feasibility Study will be examined. The photochromic dyes recommended will also be examined.

Title: GFFC Instrument Development and Spacelab 3 Mission Activities

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Significant Accomplishments FY81:

Instrument Hardware: The FY81 work effort was devoted to final fabrication and testing and checkout. At the beginning of the reporting period, engineering design changes and repairs were being made to correct structural failures that occurred during vibration tests of the GFFC performed prior to the beginning of the reporting period (July 1980). The failures consisted of 1) a weld failure which bonded the LED data display housing to the GFFC optical system, 2) failure of the oil bellows support rack, and 3) failure of GFFC oil bellows. The fixes for these failures, which resulted from a review held at MSFC, consisted of 1) improving the weld of the LED housing to the GFFC optical system, and adding structural members between the LED housing and the instrument proper to provide more rigidity, 2) adding structural strength to the oil bellows housing and 3) repair of the failed oil bellows and performance of leak tests on the bellows that did not fail to assure a set of four functioning oil bellows. EMI testing and final shake tests are now underway.

In February 1981, Dr. John Hart and Dr. Juri Toomre, visited the Aerojet facility at Azusa, California to review progress on the instrument, obtain test data film, and inspect the GFFC instrument. It was concluded that a number of minor changes were needed. These included electronic filters to stabilize the LED display readouts of GFFC sphere temperature, light filters to balance the north-south and east-west shadowgraph film grayness for recovering temperature field data, modification of the LED display readout to indicate picture type (N-S, E-W, of photochromic dot picture), replacement of a Zener diode so as to reduce voltage level associated with ultraviolet flash to excite photochromic dyes and hence reduce the intensity of the ultraviolet light to preclude over exposure

of the photochromic substance in the working fluid. As a result of discussions between the instrument scientist, lead engineer, and Aerojet, the corrections required by the GFFC Science Team were incorporated by the Aerojet without incurring additional costs.

As a result of EMI tests performed prior to February 1981, six temperature sensors located below the surface of the inner sphere failed. However, because of redundancy (two sensors at each latitude), the GFFC still has temperature measurement capability and hence control at each of the inner sphere latitudes at which the GFFC heaters are located. However, it was noted by Aerojet that the temperature sensors in question failed at a temperature a few degrees higher than $45^{o}C$. As a result Aerojet has constrained instrument operation to temperatures of $45^{o}C$ and below. The design requirements call for a GFFC which can provide inner sphere operating temperatures as high as $55^{o}C$ and automatic shut-down capability when inner sphere temperatures exceed $60^{o}C$. The fix that has been agreed upon by the Science Team, Spacelab Payloads Project Office, and NASA Headquarters consists of 1) testing the instrument for period of 30 hours and accepting it if no further temperature sensor failures occur and 2) including software and hardware to sense a failed sensor on-orbit and shut-off the heater at the latitude where the failure occurs so that experiments can still be performed in the unlikely event of additional failures on-orbit, otherwise a runaway heating condition will occur at the failed latitude.

Data Management Plan: A data management plan has been prepared and has been mailed out for review by the Science Team and appropriate NASA management. The data management plan encompasses the total GFFC project including software development, computer purchases, ground-based tests, data flow, postflight data analysis, documentation, and archiving of the GFFC flight film along with experiment descriptions and information concerning the thermodynamic and dynamic state of the Spacelab/Orbiter during the GFFC experiments on the Spacelab 3 Mission.

Preparations for Bringing GFFC to MSFC: Preparations for bringing the GFFC instrument to MSFC have been underway since the first of this calendar year. Dr. Fred Leslie/ES82 has been assigned the task of making these preparations. He will be the prime operator of the GFFC at MSFC. He has received the necessary MSFC training for handling flight hardware. A list of equipment to support ground based tests has been prepared with the lead engineer. This list includes a power supply, an air flow source, air ducting, semiconductor chips, instrument programming equipment, etc. In addition, a clean room has been identified in Building 4487 (Room B173) for performance of ground based tests and storage of the instrument.

Spacelab 3 Mission Interfaces: Work progressed smoothly during the reporting period relative to assuring that GFFC/SL3 interfaces were satisfied. A key milestone was the baselining of the GFFC Experiment

Requirements Document (ERD). As a result the SL3 Mission has accepted our requirement of 84 hours of on-orbit GFFC operation time. The current SL3 timeline accommodates this requirement.

Current Focus of Research Work:

The current work activity is aimed at implementing the hardware/software changes and performing the necessary tests to resolve the technical issues centering on the failed temperature sensors and completing the EMI and shake tests.

Plans for FY82:

During FY82 we plan to 1) complete the work associated with testing the inner sphere temperature sensors and completion of the software/hardware to accommodate temperature sensor failures on-orbit, 2) participate in the SL3 Integrated Design Evaluation (IDE) and satisfy SL3/GFFC milestones, and 3) complete the necessary preparations to bring the GFFC instrument to MSFC and 4) initiate GFFC tests at MSFC to support Science Team activities.

Title: Studies of Solar and Planetary Convection for GFFC

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Significant Accomplishments FY80:

1. Several fully non-linear, three-dimensional, unsteady numerical simulations of flows expected in the Geophysical Fluid Flow Cell were completed. Common to all these integration are hemisphericity (with a horizontal insulating barrier at the equator), $1/r^5$ gravitational acceleration, rotation, and spherically symmetric heating (hot inner sphere, cool outer sphere). The general conclusion from these studies are:

a) Flows for $1/r^5$ gravity are almost indistinguishable from those with $1/r^2$ or constant acceleration.

b) For moderate to high Taylor number (30,000 to 300,000) and moderately supercritical Rayleigh number, the differential rotation is only significant at high latitudes. There, it is a result of Coriolis turning on East-West oriented cells. Rigid walls lower eddy velocities and reduce any Reynolds' stress driven equatorial acceleration.

c) The dominant eddy type for the cases described in b) are North-South rolls in equatorial region (cell scale approximately equal to fluid layer depth), and quasi-East-West rolls at high latitudes.

2. A two-dimensional numerical simulation of compressible thermal convection of a non-rotating gas was completed. The general aspects of convection are only slightly modified from the Boussinesq (incompressible) case providedthe atmosphere is less than about five scale heights deep. (The rigorous

Boussinesq limit implies depths substantially less than a scale height.) These results give us confidence in extending GFFC results to fundamental processes in planetary atmospheres.

3. GFFC, theoretical, and other laboratory models of convection all suggest that the dominant horizontal convection scale is on the same order as the fluid depth. However, satellite pictures of meso-scale convection over the ocean indicate horizontal scales of motion many, many times greater than the vertical scale. An effort was made to understand this important difference. A linear stability calculation for convection that includes both latent heat release, and entrainment of stable air from aloft by microscale turbulence was completed. This calculation showed that the differential entrainment of a growing cell acts like an insulating wall (actually a 'super' insulating one) and cause the maximally growing linear disturbance to have a very large wavelength/depth ratio.

4. Software to obtain digitized data from the GFFC film was written. So far programs to re-register the image, decode diode matrix data, and digitize the Schlieren images are operational.

Plans for FY82:

The main focus of research will be concerned with ground-based testing of the GFFC instrument. Experiments will be carried out at Aerojet, and later at Marshall, that include runs in the inverted/stable mode with the hot inner sphere above the cool outer sphere in the Earth's gravitational field. In this configuration the motions are expected to be slow and axisymmetric for a wide range of external parameters. Thus comparisons can be made with existing theoretical models for convective flow in enclosed cavities, models that have already been verified by comparisons with experiment. This exercise will allow us to exercise the data reduction/analysis system and to calibrate the optical Schlieren system on the GFFC.

We shall attempt to do some low resolution 3-d numerical models of GFFC convection at moderate to high Taylor numbers and high Rayleigh number (Ra~600,000). It is hoped that this parameter setting will lead to a larger amount of Reynold's stress driven equatorial acceleration than previous cases that had only modest supercriticallity.

The model of compressible convection shall be extended to three dimensions, to see if compressibility can influence the plan-form selection mechanisms.

Other calculations will be carried out as the need arises. For example, we anticipate that if the orbit axis of SL3 is shifted off the current 5^{o} out of plane band in response to the needs of ATMOS, we will have to re-assess the possible occurrence and amplitude of precessionally driven motions in GFFC.

Publications:

Hathaway, D., P. A. Gilman, J. A. Toomre. Convective instability when the temperature and rotation vector are oblique to gravity, Part II. Real Fluids with Effects of Diffusion. Geophysical and Astrophysics Fluid Dynamics. Vol. 15, page 71.